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THE HORSEPOWER OF AIRCRAFT ENGINES AND THEIR MAXIMUM FRONTAL AREA

By Michel Précoul

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By Michel Précoul

A recent issue of the Russian Review "La Technique de la Flotte aerienne" contains an article by Gorochtenko concerning the effect of maximum frontal area of aircraft engines on the aerodynamic efficiency of the developed horsepower.

The trend in air-cooled engine design is toward greater horsepower simultaneously with a reduction in maximum frontal area, particularly in the diameter of 500- to 600-horsepower radials.

In the first category we find, for example, the Hispano-Suiza 14 Hars as a two-row radial of 1,100 horsepower at 2,900 m (9,500 ft.), and the Gnome-Rhone 14 Kfs of 900 horsepower at 3,620 m (11,875 ft.). In the second group the same marks apply to an engine of 680 horsepower at 4,000 m (13,124 ft.) (the Hispano-Suiza 14 Hbr) and of 1.02 m (3.35 ft.) diameter; and an engine of 570 horsepower at 4,000 m (Gnome-Rhone) of 0.96 m (3.15 ft.) diameter.

A reduction in maximum frontal area, even at the expense of horsepower, is vital in view of the substantial rise of speed of modern aircraft. The importance attaching to this reduction is particularly well illustrated by the world's speed record, broken in 1934 by a Caudron airplane mounting a 400-horsepower inverted, in-line Renault engine of very small frontal area, whereas the previous record had been broken with a radial engine, of more than 1 m (3.28 ft.) diameter, developing almost 1,000 horsepower.

Qualitatively, the problem is plainly put: In a fast single-seater (a pursuit, for instance), the maximum fuselage frontal area is governed by the size of the pilot, for whom about 7.53 to 8.61 sq.ft. are sufficient. Now, the Wright Cyclone 1280 F 3 of 720 horsepower, for example,

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*"La puissance des moteurs et leur maitre-couple." L'Aéronautique, No. 207, August 1936, pp. 107-111.

has a diameter of 1.37 m (4.49 ft.), which gives the fuselage a maximum cross section which, frankly, is too great: 1.47 m^2 (15.82 sq.ft.). The power of the engine is, in consequence, utilized in its larger extent to overcome its own drag.

The effect of reducing the maximum cross section of an engine is, in general, not only a reduction in body drag, but also a drop in horsepower, engine weight, and consequently, the total weight of the airplane. The analytical problem, though complicated, may be simplified by assuming the landing gear to be retractable, so that only the drag of fuselage, wings, and tail remains.

Gorochtenko's study gives an interesting method of calculation, which analyzes the various factors. The account which follows is an adaptation of it.

METHOD OF CALCULATION

The thrust equation may be written:

$$75\ W\ \eta = \rho\ C_{xa}\ S_p\ V^3 \tag{1}$$

where W is the horsepower

C_{xa}, airplane drag

S_p, wing area

η, propeller efficiency

ρ, a/g

Applied to a cantilever monoplane with retractable landing gear, we may write:

$$C_{xa}\ S_p = C_{xp}\ S_p + C_{xe}\ S_e + C_{xf}\ S_f$$

where the subscripts p, e, and f refer to the drag and areas of wing, tail, and fuselage, respectively. Assuming that $C_{xp} = C_{xc}$, by putting

$$k = \frac{S_p + S_e}{S_p} > 1$$

while denoting the total weight of the airplane by P_t and the load per m² with p, we readily obtain:

$$W = \frac{\rho V^3}{75 \eta}\left[\frac{k P_t}{p} C_{xp} + S_f C_{xf}\right] \tag{2}$$

On the other hand, posing:

$$u = \frac{P_t}{P_u + P_m}$$

where P_u is the useful load

P_m, engine weight

m, weight of engine per horsepower

and $q = mu$

we have $P_t = u P_u + u P_m = u P_u + q W$

Lastly, when writing $A = \rho V^3/75\eta$, formula (2) becomes:

$$W = \frac{\dfrac{k C_{xp} u P_u}{p} + C_{xf} S_f}{\dfrac{1}{A} - \dfrac{k q C_{xp}}{p}} \tag{3}$$

Given the load per m², the wings, the propeller, and the airplane speed, the following terms in formula (3) are constant:

$$A = \frac{\rho V^3}{75 \eta} = \text{const.}$$

$\dfrac{kq C_{xp}}{p}$ = const. (for u and m constant); u depends very little on W; m exacts the same weight per horsepower of the engines on which the choice is to be made. Thus, a change in engine does not affect the denominator of the term at the right side and, posing again

$$\frac{k C_{xp} u P_u}{p} = T$$

for two engines of unlike power and maximum cross sections but giving an identical airplane speed V, we have:

$$\frac{W}{W_1} = \frac{T + C_{xf}\, S_f}{T + C_{xf}'\, S_f'}$$

whence

$$W_1 = W\,\frac{T + C_{xf}'\, S_f'}{T + C_{xf}\, S_f} \qquad (4)$$

It will be noted that this formula disregards the reduction in propeller-engine interference due to the diminution in maximum cross section. Still this entails a reduction in horsepower; consequently, for an identical speed and identical propeller diameter, the efficiency varies fairly little. On the other hand, this formula, by assuming T = const., poses P_u = const. Now, the reduction in horsepower lowers the weight P_t; this error is, however, not very great and can only act beneficially on higher powered engines and at larger maximum cross sections which, as we shall see, give less interesting results.

PRACTICAL APPLICATION OF FORMULA

The use of formula (4) for finding the best engine for a given airplane and for a certain speed V evolves on the knowledge of the value of T. A general comparative study of existing airplanes can, meanwhile, supply T values which are accurate enough for a preliminary project. The following tabulation gives the T values for divers airplanes:

Type	K	100 C_{xp}	p_u, kg	p, kg/m²	u	T
Modern pursuit	1.3	0.55	400	100	1.75	0.05
Heavily loaded pursuit	1.3	0.55	500	125	1.75	0.0625
Pursuit, aerodynamically very clean, thin profile	1.25	0.45	400	100	1.7	0.0380
Racer	-	-	250	100	-	0.017
Fast observation	-	-	750	-	-	0.072-0.094

kg x 2.20462 = lb.   kg/m² x 0.204818 = lb./sq.ft.

As to C_{xf}, it ranges between 0.09 and 0.1 for aircraft with radial engine, fitted with N.A.C.A. cowling (C_{xf} is susceptible to reduction to 0.07-0.08), while for the record airplanes, type Caudron 460, it ranges between 0.035 and 0.040. On comparing radial engines it may, moreover, be conceded that $C_{xf} = C_{xf}'$.

The comparative study of engines to be adapted to an airplane can be greatly facilitated by the use of curves of the kind shown in figure 1.

In this chart the ratios W_1/W are plotted against S_f (maximum cross section) and D (diameter of engine) for various values of T and C_{xf}. The engine of W horsepower (W hp.) has been taken with 1 m (3.28 ft.) diameter and 0.785 m² (8.45 sq.ft.) maximum cross section. The importance of S_f is readily noted. On every curve T the speed is constant, but it is observed that an engine of $D = 1.375$ m (4.51 ft.) ($S_f = 1.5$ approx.) of W_1 hp. (with $W_1/W = 1.48$) for $T = 0.05$ and $C_{xf} = 0.08$ gives a speed equal to that obtained with an engine of only W hp. $\left(\frac{W_1}{W} = 1\right)$ but having a $D = 1$ m (3.28 ft.) and $S_f = 0.78$ m² (8.4 sq.ft.) approximately. Or, in other words, if the engine W_1 was a Wright Cyclone 1820 F 3 of 700 hp. ($D = 1.37$ m), an engine of only 465 hp. but with $D = 1$ m (for a pursuit airplane) or even an engine of 420 hp. with $D = 1$ m (record airplane), would give the same speed as the airplane in question.

Suppose the engine is mounted in the wing and the airplane has no fuselage; then with W_0 as the horsepower of the engine, we have:

$$\frac{W}{W_0} = 1 + \frac{C_{xf}\ S_f}{T}$$

plotted in chart 2 for various C_{xf}/T. This type of chart permits at the same time the calculation of chart 1. Simply take on figure 2, the values W/W_0 and W_1/W_0 and make the division.

COMPARISON OF ENGINES OF DIFFERENT WEIGHT PER HORSEPOWER

Formula (4) is inapplicable if the weight per horsepower of the compared engines is not the same.

Formula (3) may be expressed in the form

$$W = A \left(T + T \frac{P_m}{P_u} + C_{xf}\ S_f\right)$$

so that

$$W_1 = W \frac{1 + \frac{P_m'}{P_u} + \frac{C_{xf}'\ S_f'}{T}}{1 + \frac{P_m}{P_u} + \frac{C_{xf}\ S_f}{T}} \tag{5}$$

This formula (5) then makes it possible to fix the choice of engine quite definitely. To illustrate: For a pursuit airplane of

$$T = 0.045$$

$$P_u = 400 \text{ kg}$$

$$C_{xf} = 0.09$$

with a Gnome-Rhone engine, type 14 Kdrs, of

$$P_m = 596 \text{ kg}$$

$$D = 1.29 \text{ m}$$

$$W = 800 \text{ hp. at } 3,850 \text{ m}$$

formula (5) gives:

$$1 + \frac{P_m}{P_u} + \frac{C_{xf}\ S_f}{T} = 5.09$$

With a Wright Cyclone 1820 F 3, of $P = 430$ kg (948 lb.) and $D = 1.37$ m, mounted in the same airplane, formula (5) gives:

$$1 + \frac{P_m'}{P_u} + \frac{C_{xf}'\ S_f}{T} = 5.03$$

and consequently,

$$W_1 = 800 \frac{5.03}{5.09} = 790 \text{ hp.}$$

That is, to develop the same speed at 3,850 m (12,630 ft.) as that supplied by the Gnome-Rhone K 14 engine, the Wright Cyclone should have 790 hp., whereas it actually develops only 720 hp. at 2,200 m (7,218 ft.) and so, definitely establishes the superiority of the Gnome-Rhone 14 K (provided the airplane weight is the same).

Similarly, for a twin Wasp Junior WR 605 of 700 hp. at 2,700 m (8,858 ft.), weighing 450 kg (992.08 lb.) and with $D = 1.11$ m, we have:

$$W_1 = 800 \frac{4.05}{5.09} = 636 \text{ hp.}$$

But at 3,850 m, the Wasp has only 615 hp. available against 800 hp. of the K 14. However, the calculation suggests that the Wasp - if it had 636 hp. available at 3,850 m - would (by virtue of its much smaller diameter) develop the same speed as the K 14. These two engines are aerodynamically comparable.

RADIAL VERSUS INVERTED IN-LINE ENGINES

Formula (5) equally makes it possible to define the characteristics of an air-cooled, inverted in-line engine which gives at 5,000 m (16,400 ft.), in a pursuit, say, a speed equal to that developed by the Gnome-Rhone 14 Kdrs which, at this height, has 695 hp. available. With

$$P_u = 350 \text{ kg (772 lb.)}$$

and

$$T = 0.033$$

the C_{xf} of an airplane with inverted in-line engine, will be 0.04; the maximum cross section, 0.7 m² (7.53 sq.ft.; for a weight of 200 kg (441 lb.), its power at 5,000 m (16,400 ft.) should be:

$$W_1 = 695 \frac{2.42}{6.25} = 269 \text{ hp.}$$

This result is surprising and supplies the theoretical explanation of the speed record of the Caudron Renault of 400 hp., beating the previous record held by the United States, with more than 900 hp. (radial engine). But, in all fairness it is necessary, in this case, to take the reduction in fuel weight into consideration, assuring the same range. This weight is supposed to be proportional to the change in total airplane weight.

With $P_u = P_c + P_\nu$, (P_c being fuel weight and P_ν the rest of the useful load), we have:

$$\frac{P_\nu' + P_c' + P_m'}{P_\nu + P_c + P_m} = \frac{P_c'}{P_c} = \frac{P_t'}{P_t}$$

$$\frac{\Delta P_c + \Delta P_m}{P_u + P_m} = \frac{\Delta P_c}{P_c}$$

whence

$$\Delta P_c = \frac{\Delta P_m \, P_c}{P_u + P_m - P_c} \qquad (6)$$

If, for an airplane fitted with an engine of W hp., we give it P_u and T, we have, for an airplane equipped with an engine of W' hp. ($W' < W$):

$$P_u' = P_u - \Delta P_c$$

and formula (5) becomes:

$$W_1 = W \frac{T' + T' \dfrac{P_m'}{P_u'} + C_{xf}' \, S_f'}{T + T \dfrac{P_m}{P_u} + C_{xf} \, S_f} \qquad (7)$$

Formula (6) gives ΔP_c; P_u' and T' are readily obtainable from W_1 by means of formula 7.

Reverting to the last calculations in which the Gnome-Rhone K 14 is compared with an in-line engine weighing 200 kg (440.92 lb.) and assuming that the 14 Kdrs requires a weight P_c of 150 kg (330.69 lb.) for $P = 350$ kg (771.62 lb.), we have:

$$P_c = 74 \text{ kg } (163.14 \text{ lb.}), \quad P_u' = 276 \text{ kg } (608.48 \text{ lb.})$$

$$T' = \frac{0.033 \times 276}{350} = 0.0260$$

and equation (7) gives:

$$W_1 = 695 \, \frac{0.0728}{0.2062} = 245 \text{ hp.}$$

Tabulation of the Characteristics of Various Modern Engines
Reduced to 5,000 m (16,400 ft.)

Engine	Type	Diameter (m)	Weight (kg)	Horsepower (hp.) (m)	Actual hp. at 5000 m	Fictitious hp. at 5000 m	Difference between real and fictitious hp.
Gnome-Rhone 14 Kdrs	2-row radial	1.29	596	800 at 3850	695	695	0
Gnome-Rhone 14 Kfs	2-row radial	1.29	565	900 " 3620	760	684	+76
Gnome-Rhone Mars	2-row radial	0.96	374	570 " 4000	508	512	-4
Gnome-Rhone 9 Krs	1-row radial	1.29	420	620 " 4000	550	635-555	-85 to -5
Hispano-Suiza 14 Hars	2-row radial	1.25	600	1100 " 2900	855	676	+120
Hispano-Suiza 14 Hbrs	2-row radial	1.00	458	680 " 4000	603	506	+97
Pratt Whitney Twin Wasp JW 610	2-row radial	1.22	531	800 " 2140	570	637	-67
Pratt Whitney Twin Junior WR 605	2-row radial	1.11	450	700 " 2740	535	554	-19
Wright Cyclone RI 510 C 3	2-row radial	1.14	450	637 " 4700	615	568	+ 47
Wright Cyclone I 820 F 3	1-row radial	1.37	430	720 " 2200	515	686-598	-171 to -83
Wright Cyclone F-53	1-row radial	1.37	427	750 " 3350	615	684-596	-69 to 19
Renault Bengali 6 Pdis	inverted in-line	Sf. 0.7	220	220 " 4000	195	240	-45

m × 3.28083 kg × 2.20462 = lb.

The previously obtained value of W_1 was 269 hp., so the reduction corresponding to the lightening allows a gain of 24 hp. while still obtaining the same speed.

THE QUALITY OF AIRPLANES

Further, the reduction in horsepower required improves the quality of the airplane. In effect, with K' and K as the optimum qualities, and C_p as wing drag, we have:

$$\frac{K'}{K} = \sqrt{\frac{KC_p + \frac{C_{xf}\ S_f}{S}}{KC_p + \frac{C_{xf}'\ S_f'}{S'}}} = \sqrt{\frac{KC_p + \frac{C_{xf}\ S_f p}{u(P_m + P_u)}}{KC_p + \frac{C_{xf}'\ S_f p}{u(P_m' + P_u')}}}$$

$$K = 1.3$$

$$C_{xp} = 0.004$$

$$u = 1.7$$

$$p = 100$$

$$P_u = 350$$

$$P_m = 276$$

which gives:

$$\frac{K'}{K} = 1.2$$

Since the fuel consumption is proportional to the quality - assuming the same range - the light engine lowers P_c 1.2 times more; that is, to say, P = 63 kg (138.89 lb.) rather than 76 kg (167.55 lb.). Then

$$P_u = 263 \text{ kg } (579.82 \text{ lb.})$$

$$T = 0.0248$$

and

$$W_1 = 695 \frac{0.0716}{0.2063} = 240 \text{ hp.}$$

In brief, this calculation shows that when we can design a light engine of 240 hp. at 5,000 m, it can carry a light pursuit airplane at the same speed as that actually obtained with a Gnome-Rhone K 14.

ENGINES OF EQUAL HORSEPOWER

Let us point out that formula (5) also enables us to establish the relationship existing between a weight increase and a decrease in diameter for engines of equal horsepower giving the same speed in an airplane. It is

$$W' = W$$

then formula (5) reduces after some transformations to

$$\Delta P_m \,\% = \Delta S_m \,\% \,\frac{C_{xf}\; P_u\; S_m}{T\; P_m} \qquad (8)$$

This formula shows that, when maintaining constant speed, an increase of 1 percent in weight of, say, the Gnome-Rhone 14 Kdrs, exacts a 0.57-percent reduction in maximum cross section; in actual figures, for P_m of approximately 600 kg (1,323 lb.), with which for $\Delta P_m = 6$ kg ΔD becomes only equal to 0.04 m (1.57 in.).

CONCLUSION

Our adaptation of the Russian report reveals the effect of maximum cross section of an engine as well as the interest attaching to a choice not based solely on horsepower. The tabulation (p. 9) gives a comparison between different engines restored at 5,000 meters. The last column but one gives the horsepower which engines of the same weight and diameter should have in order to give a pursuit airplane with

$T = 0.045$ (for the Renault 6 P dis: $T = 0.033$)

$P_u = 400$ kg (" " " $P_u = 350$ kg)

$C_{xf} = 0.09$ (two-row radial)

$C_{xf} = 0.08$ (one-row ")

$C_{xf} = 0.07$ (Napier Dagger)

the same speed as with a Gnome-Rhone 14 Kdrs (formula W_1/W).

Translation by J. Vanier,
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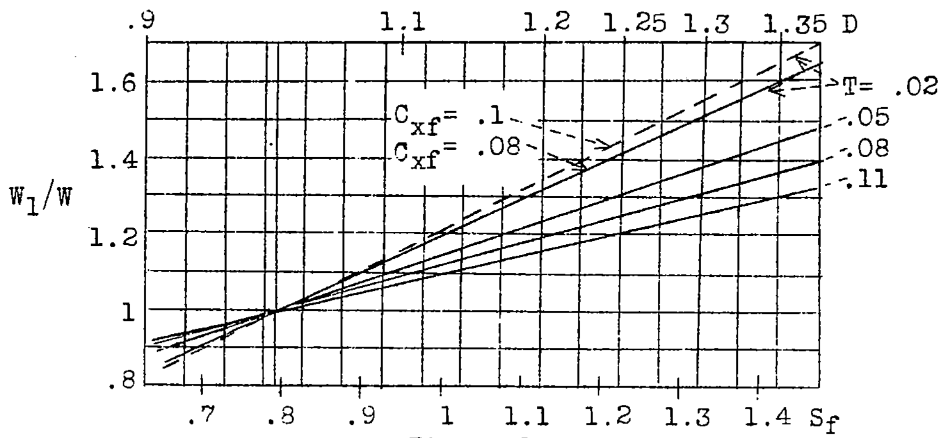

Figure 1

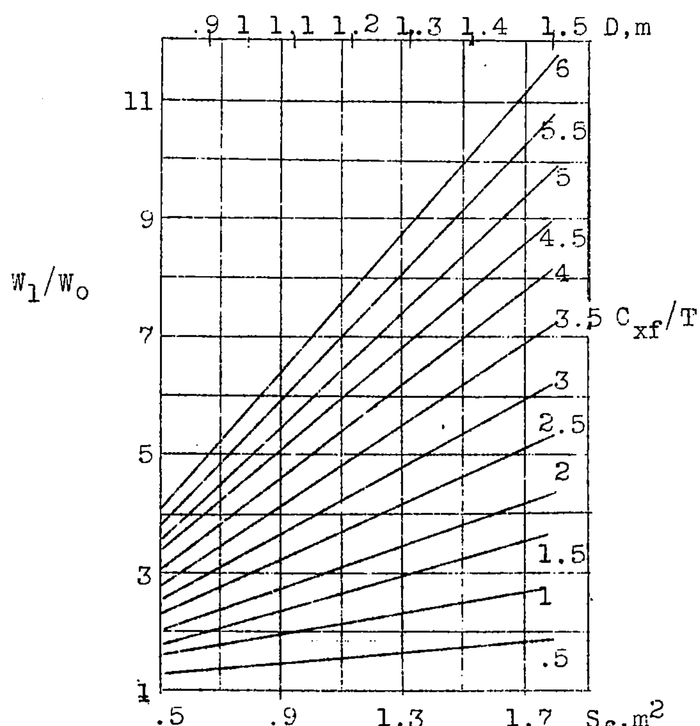

Figure 2